An Experimental Study on the Defrosting Performance of a PCM-Based Reverse-Cycle Defrosting Method for Air Source Heat Pumps

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ABSTRACT

When an ASHP operates in heating mode, frost can be accumulated on the surface of its outdoor coil. Currently the most widely used defrosting method for ASHPs is reverse cycle defrost. However, the fundamental problem for such a method is that there is insufficient heat available for ASHPs during defrosting.

This paper reports on an experimental study of developing a novel reverse-defrosting method which is thermal energy storage (TES) based using phase change material (PCM). Comparative experiments were carried out at two operating conditions: standard defrosting condition and the PCM-based defrosting condition. Results indicated that the use of this PCM-based reverse defrosting method could help shorten defrosting time, improve indoor thermal comfort for occupants, as compared with the use of standard defrosting method. Furthermore, the experimental results also suggested that storing heat in PCM would not degrade the quality of space heating provided by the ASHP during heating operation.

1. INTRODUCTION

When an air source heat pump (ASHP) unit operates for space heating at a low ambient temperature in winter, frost formed on the tube surface of its outdoor coil becomes problematic, because frost reduces the airflow passages area and acts as a thermal insulator, leading to the performance degradation for the outdoor coil, or even the shutdown of the ASHP unit. Therefore periodic defrosting becomes necessary. Currently, the most widely used standard defrosting method for ASHPs is reverse-cycle defrost (Ding et al., 2004; Byun et al., 2006). When a space heating ASHP unit is operated at a reverse-cycle defrost mode, its outdoor coil acts as a condenser and its indoor coil as an evaporator. Also, during defrosting, the indoor air fan in an ASHP unit is normally switched off to avoid blowing cold air directly to a heated indoor space, affecting thermal comfort of occupants. Therefore, there is an insignificant amount of energy available indoor air because of a negligibly small airside convective heat coefficient when the indoor air fan is turned off during defrosting. Hence, the energy available for defrost is basically that stored in indoor coil metal. When there is no heat to be absorbed from the coil metal (i.e., when coil temperature drops to a sufficiently low level), evaporating temperature significantly drops. In this case, the energy to melt frost mainly comes from the input work to compressor and is not sufficient for quick defrosting. Insufficient heat available during defrosting is currently a fundamental problem as far as reverse-cycle defrost is concerned, with which a number of operational problems during defrosting for ASHPs are associated. These include a prolonged defrosting time when a lower indoor air temperature inside a heated space can be resulted in since no heating is provided during defrosting, so that the thermal comfort of occupants can be adversely affected. Furthermore, because an indoor coil is at a very low temperature immediately after the completion of defrosting, it would take a longer time to heat up the coil first before space heating can become available. This further lengthens the time period without heating supply.

Although previous research related to both frosting and reverse-cycle defrost for ASHPs have been carried out and reported, they are mainly for system modeling (Krakow et al., 1993; Yao et al. 2004), or for improving the operating characteristics of ASHPs (Anandet al. 1989; O'Neal et al. 1991; Nutter et al. 1996; Jhee et al., 2002; Watters et al. 2002; Huang et al., 2004; Guo et al. 2008). The fundamental problem of insufficient heat available during reverse-cycle defrosting remains unsolved.

To solve the fundamental problem of insufficient heat available during reverse-cycle defrost, so as to enable a quick defrost process and consequently to ease off the adverse impact on occupants' thermal comfort, a novel thermal energy storage (TES) based reverse-cycle defrosting method using phase change material (PCM) has been developed. Controlled comparative experiments using a purposely built experimental setup, with the same frosting conditions but under either the standard reverse-cycle defrosting method or the novel PCM-based reverse-cycle defrosting method, were carried out. The experimental results suggested that the use of the novel PCM-based reverse-cycle defrosting method can help shorten defrosting period and improve indoor thermal comfort for occupants during defrosting and re-heating process while without degrading the quality of space heating provided by the ASHP during heat operation.

2. THE NOVEL TES-BASED REVERSE-CYCLE DEFROSTING METHOD AND THE RELATED EXPERIMENTAL SETUP

2.1 The experimental setup and its instrumentation

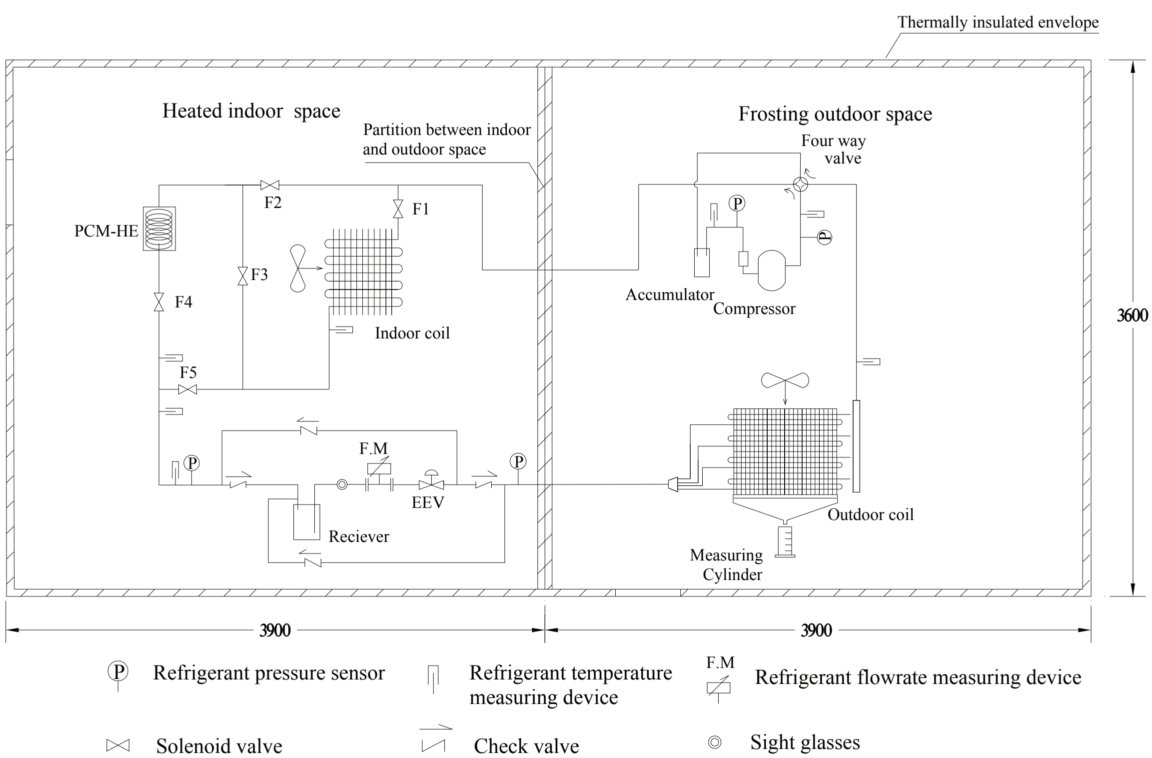

Fig. 1 Schematic diagram of the experimental setup

An experimental setup where the novel PCM-based reverse-cycle defrosting method could be realized was specifically developed. The setup mainly consisted of an experimental prototype (EP) of ASHP unit and an existing environmental chamber. The EP was modified from a commercially available 6.5 kW heating capacity variable speed ASHP and was installed inside the existing environmental chamber. The chamber was divided into a heated indoor space and a frosting outdoor space, each measuring at 3.9m (L) ×3.8m (W) ×2.9m (H), separated by a thermally insulated partition. The indoor coil of the EP was installed inside the heated indoor space and the outdoor coil of the EP inside the frosting outdoor space, as shown in Fig.1 which shows the schematics of the experimental setup. The experimental ASHP was a split-type unit consisting mainly of a swing type compressor, an accumulator, a four-way valve, an electronic expansion valve, a multi-circuit indoor coil and a multi-circuit outdoor coil. As seen in Fig.1, a PCM-based heat exchanger (HE) and five solenoid valves (F1 to F5) were added to the indoor coil side of the EP.

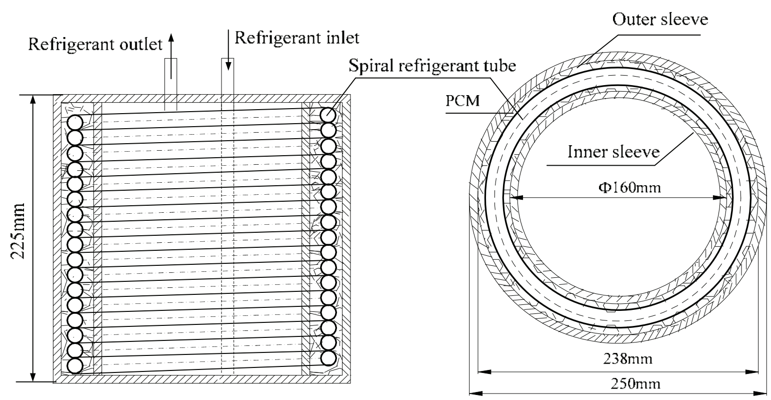

Fig. 2 Detailed structure of the PCM based heat exchanger used in the EP

The PCM-HE was designed as a thermally insulated shell-and-tube storage unit with the PCM on the shell side and the refrigerant being circulated inside the tubes. The detailed structure of the PCM-HE used in the EP is shown in Fig. 2. $CaCl_2{\cdot}6H_2O$ was used as PCM with melting point of 29 ^oC and latent heat of fusion of 190.8 kJ/kg. It can be therefore seen that with the addition of the PCM-HE, the refrigerant first flows through the indoor coil then the PCM-HE if the valves F1, F3, F4 are in open position. The PCM melts by absorbing heating from sub-cooled refrigerant. In this way, heat stored in the PCM-HE can be used for defrosting when needed. This can help provide sufficient heat for defrosting to enable a quick defrosting, thus the disturbance to occupants' thermal comfort during a reverse-cycle defrost process can be alleviated.

The existing environmental chamber in the experimental setup had a separate air conditioning (A/C) system and sensible and latent load generating units (LGUs), so that suitable testing conditions in both indoor and outdoor spaces may be maintained. The indoor air dry-bulb temperature and RH were obtained by using the existing measuring instruments of the environmental chamber. On the other hand, pre-calibrated K-type thermocouples (of ±0.3^oC accuracy) were used for measuring the temperatures of surfaces of the outdoor coil. The refrigerant pressures were measured using pressure transmitters with an accuracy of ±0.3% of full scale reading and the refrigerant mass flow rate by a variable area flow (accuracy of ±1.6%). Five temperature sensors (PT1000, Class B) were fixed evenly at the outlet of indoor coil to measure the dry-bulb temperature of supply air. All sensors and measuring devices used in the experimental setup were able to output direct current signal of 4-20 mA or 1-5 V, which were transferred to a data acquisition unit for logging and recording. A data acquisition system was used to collect and record all the measured data throughout an experimental process at an interval of 5 s.

2.2 Comparative experiments: mode and procedures

The comparative experiments were carried out in the following two operation modes:
Mode A: Standard heating and reverse-cycle defrosting operation mode (baseline mode)

During the standard heating operation, both F1 and F5 were in open position. When defrost was needed, the four way valve was reversed. The experimental results obtained in this operation mode would provide a base for comparison.

Mode B: The PCM-based heating and reverse-cycle defrosting operation mode

After 10 min of standard heating operation, valves F1, F3 and F4 in open position, and the hot refrigerant gas flowed through the indoor coil first and then the PCM-HE. When the four-way valve was reversed, defrost was initiated with valves F2 and F4 were in open position, and the PCM-HE actually acted as an evaporator. The energy stored in PCM was discharged and used to melt the frost on the outdoor coil surface.

For modes of A and B, the air temperature and RH inside the heated indoor space were firstly maintained at 22 ºC and 50%, respectively, jointly by the use of EP, the existing A/C system and LGUs. Then the output of the existing A/C system and LUGs were fixed during the whole frosting/defrosting cycle. The EP was then operated in the heating (or frosting) mode for 1.5 hours during heating operation (Mode A) or heating and heat storage operation (Mode B), the frosting outdoor space in the experimental setup was maintained at 0 ± 0.1 ºC (dry-bulb) and at 90% ± 3% relative humidity, jointly by the use of both EP and the LGUs placed inside the outdoor space, to simulate an outdoor environment for ASHP so that frost can be formed on the surface of outdoor coil. Due to safety reason, at the end of a frosting (i.e., heating or heating and storage) operation, compressor was switched off for one minute. After that, the 4-way valve was reversed to defrosting mode. Four seconds later, the compressor was turned on again and a defrosting operation started.

Defrosting operations were manually terminated when the tube surface temperature of the lowest refrigerant circuit in the outdoor coil reached 18 ºC (Ding et al., 2004; Huang et al., 2004; Payne and O'Neal, 1995). Both the indoor air fan and the outdoor air fan during defrosting operations were turned off. After a defrosting operation was manually terminated, also for safety reason, the compressor was turned off for one minute. Then the 4-way valve was reversed to frosting mode. Four seconds later, both the compressor and the outdoor air fan were turned on, but the indoor air fan remained off for further 3 minutes to avoid blowing cold air directly to the indoor heated space, when the indoor coil was still at a low temperature. When the indoor air fan was turned on, the EP was in heating operation again.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 System dynamics during defrosting process

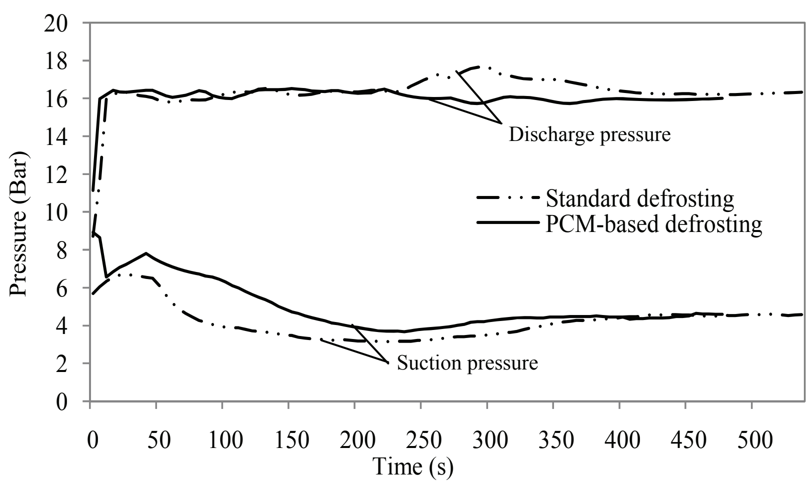

Fig.3 Measured compressor discharge and suction pressures in the comparative experiments during defrosting process

While maintained the same frosting outdoor condition and the same frosting operation time as described previously, the PCM-based defrosting performance was different from the standard defrosting, which are shown from Fig.3 to 6.

The defrosting durations in Mode A and Mode B were 535s, and 475s, respectively. Therefore, defrosting duration can be shortened by 11.2% when the novel PCM-based reverse-cycle defrosting method was used, as compared to the use of the standard reverse-cycle defrost.

Fig.3 shows the measured variation profiles of compressor discharge pressure and suction pressure during defrosting operation. The measured compressor discharge pressures in both methods were maintained at ~ 16bar. However, the suction pressure in mode B was always higher than that in Mode A. It was due to the fact that in PCM-based defrosting method, the evaporator was the PCM-HE where sufficient heat was stored, while in standard defrost, insufficient heat available for refrigerant in the indoor coil from nature convection of air after shut down of the indoor fan.

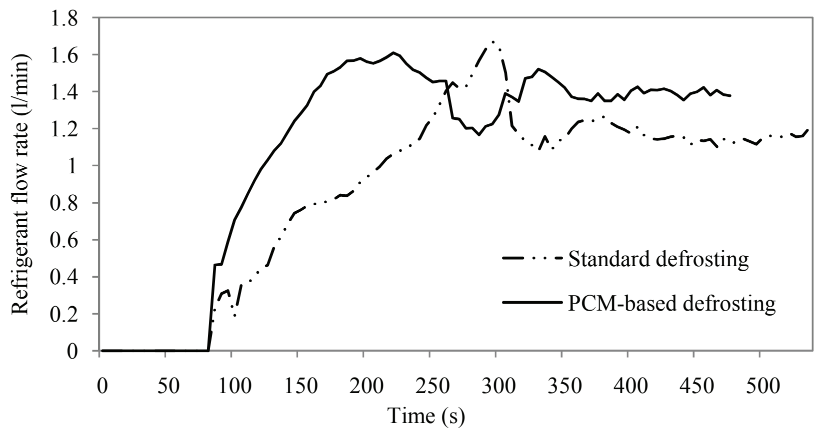

Fig. 4 Measured refrigerant flow rate in the comparative experiments during defrosting process

The refrigerant flow rate during defrosting operation is shown in Fig.4. Refrigerant flow rate in mode B was larger than that in Mode A, resulting from the higher suction pressure thus lower specific volume before compressor in PCM-based defrosting method. Besides, the refrigerant flow rate increased more quikly in PCM-based defrosting than that in standard defrost.

3.2 Airside performance during defrosting and re-heating process

Fig.5 indicates the measured indoor supply air temperautre in the comparative experiments. It should be noted that during the period between defrost starting and indoor fan starting (~13 min in Mode A and ~12 min in Mode B, respectively), the supply air temperature was actually the ambient air temperature measured at outlet of the indoor coil when the indoor air fan was switched off. As seen, in both modes, after the indoor fan was turned on, the indoor supply air temperatures experienced a sharp increase in a short period of time. This was because that before the fan was turned on, compressor was already running for 3 minutes, and the indoor coil heated. Accordingly, the air immediately surrounding the indoor coil was also heated. Therefore, after the fan was turned on, the heated surrounding air was blown off. Afterwards, the indoor supply air temperature however significantly decreased because the indoor air at a lower temperature was sucked into the indoor coil. After the indoor air temperature started to increase, as shown in Fig. 6, the supply air temperature in both modes started to increase. As seen, when PCM-based defrosting method was used, energy could be provided by PCM-HE instead of the indoor coil, which led to higher temperature on the indoor coil. While in standard defrosting method, it took longer time to resume heating when defrosting ended because of low discharge temperature (pressure) during defrosting process.

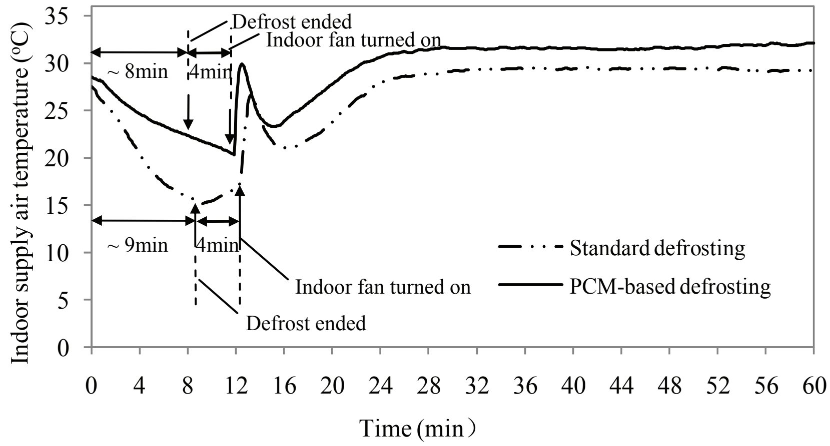

Fig. 5 Measured indoor supply air temperatures in the comparative experiments during defrosting and re-heating process

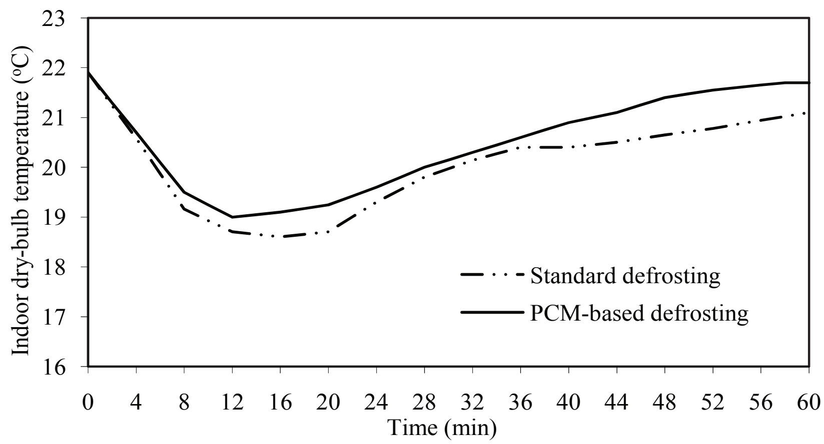

Fig.6 Measured indoor dry-bulb temperatures in the comparative experiments during defrosting and re-heating process

Fig. 6 illustrates the measured indoor dry-bulb temperature in the comparative experiments. As seen, the measured indoor air temperature in Mode B was always higher than that in Mode A, resulting from a shorter defrosting period and a higher indoor supply air temperature in Mode B. From Fig.6, the lowest indoor dry-bulb temperatures recorded in both modes were 18.6 °C (at ~16 min in Mode A) and 19.1 °C (at ~12 min in Mode B), respectively. Furthermore, it can be seen that indoor air temperatures started to rise ~20 minutes and ~12 minutes after defrosting started in Mode A and Mode B, respectively.

According to ANSI/ASHRAE Standard 55 (2004), a person's sense of thermal comfort is primarily a result of the body's heat exchange with its environment, and is determined by two personal and four environmental parameters: metabolic rate and clothing insulation; air temperature, mean radiant temperature (MRT), indoor air velocity and humidity, respectively. And in this experiment, the metabolic rate and clothing insulation for the occupants were supposed to be the same. the measured indoor RH and indoor air velocity during heating and defrosting in both modes were similar. Furthermore, the MRT was greatly related with ait temperature and air velocity. In this case, the primery parameters effecting the thermal comfort for occupants in this research was air temperature. From Fig.6, the indoor dry-bulb temperature in Mode B was always higher than that in Mode A. Moreover, , the indoor dry-bulb temperature begen to increase at 12 min in Mode B while it began to increase at 20 in Mode A. It is reasonable to conclude that by adopting PCM-based defrosting method, the indoor thermal comfort can be improved comparing with the standard defrosting method.

3.3 Airside performance during heating and heat storage process

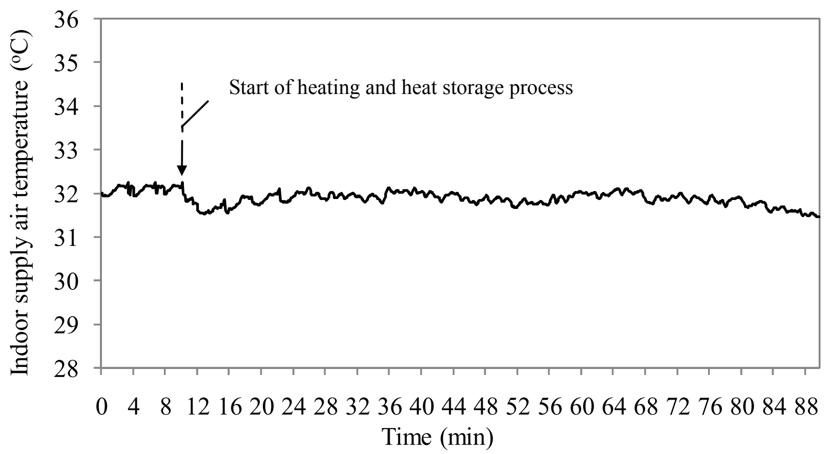

Fig.7 Measured indoor supply air temperatures during heating and heat storage process in Mode B

Fig.7 reveals the indoor supply air temperautre during heating and heat storage process in Mode B. At the first 10 min, the indoor supply air temperautre was ~32.1 ^{o}C. When the heating and heat storage process was began, the indoor supply air temperautre decreased slightly, and then the indoor supply air temperautre increased gradually to ~31.9 ^{o}C. At the end of the heating and heat storage process, the indoor supply air temperature decreased along with the frost accumulated on the outdoor coil and the performance of the heat pump system deteriorated. As seen, the heat storage process will not disturb normal heating thus not degrade the quality of space heating provided by the ASHP during heat operation due to the fact that the refrigerant first flows through the indoor coil then the PCM-HE.

4. CONCLUSIONS

To solve the fundimental problem of insufficient heat available during standard reverse-cycle defrost for ASHPs, a novel PCM-based reverse-cycle defrosting method has been developed. Comparative experiments using both the novel PCM-based reverse-cycle defrosting method and the standard reverse-cycle defrosting method were designed and carried out. The experimental results suggested that the use of the novel PCM-based reverse-cycle defrosting method would lead to a shorter defrosting process, a higher indoor air temperature, and consequently, occupants' indoor thermal comfort can be improved during a reverse-cycle defrosting. Furthermore, the heat storage process will not degrade the quality of space heating provided by the ASHP during heating operation.

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